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Multi-Mode Physical Modelling of a Drum Boiler

Daniel Bouskela[a]*

[a]*EDF, 6 Quai Watier 78401 Chatou France*

Abstract

Multi-mode modelling and simulation is the ability to switch between states that describe different operating conditions, for instance: turning subsystems on or off, phase appearance or disappearance (e.g. vapor within liquid), switching to a dysfunctional mode (e.g. pump cavitation or breakage), switching controllers, etc. Cyber-physical systems exhibit frequent mode switching. Models with multiple modes may exhibit varying structure since modes may have different levels of detail, hence different numbers of degrees of freedom or state variables. When switching modes, state variables may appear or disappear dynamically. The simulation of such systems is a fundamental difficulty that has been successfully addressed recently within the European MODRIO project by designing and implementing a new Modelica hybrid-state machine in the modelling and simulation tool Dymola. This new hybrid-state machine has been used to model phase appearance and disappearance in thermal-hydraulic volumes. The fundamental physical equations for the one-phase and two-phase modes and the conditions for transition between modes are presented and simulation results are given for the industrial test-case of a drum boiler. Thermal-hydraulic volumes are fundamental components in the staggered grid scheme used to model thermal-hydraulic systems, so the result solves the general problem of phase appearance and disappearance in thermal-hydraulic systems.

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* Corresponding author. Tel.:+33 1 30 87 84 64.
E-mail address: daniel.bouskela@edf.fr

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1. Introduction

Power plants are cyber-physical systems (CPS) that exhibit a large number of operating modes of all kinds: normal modes such as startup, shutdown or nominal operation, and dysfunctional modes such as component failures, leaks, spurious phase appearance or disappearance… Large conventional power plants such as nuclear power plants are most of the time operated under steady state conditions. However when the system is operated away from its nominal condition, modes switching occur, following planned or spurious events. The growing share of renewables on the power grid means that large conventional power plants will be more often operated away from their nominal operating point, leading to less revenue for the operator and increased wear for the plant. It also means that more spurious events may occur, originating e.g. from the power grid, leading to system faults or failures. To minimize these drawbacks, it is necessary to optimize large plant transients such as startup, shutdown, load following or islanding with respect to costs while complying with operational constraints. It is also necessary to analyze the behavior of the system in the presence of more diverse origins of faults or failures. This requires the ability to model and simulate mode switching.

Multi-mode modelling and simulation (M&S) is the ability to switch between states that describe different operating conditions. Some examples are: turning subsystems on or off, appearance or disappearance of a phase (e.g. vapor) within another phase (e.g. liquid), switching to a dysfunctional mode (e.g. pump cavitation, pump breakage, valve leakage), switching controllers, etc. CPS exhibit frequent mode switching. Transitions between modes may be deterministic (e.g. turning a subsystem on or off as required by an operating procedure), or probabilistic (e.g. breakage of a pump due to excess wear). Multi-mode M&S is necessary to be able to explore the consequences of an initiating event on the system that may lead to mode switching. It is thus necessary for designing and verifying fault-resilient systems against requirements.

Models with multiple modes may exhibit time-varying structure since modes may have different levels of description detail, hence different numbers of degrees of freedom or state variables. When switching modes, state variables may appear or disappear dynamically. Also, the physical behavior of CPS modes are best described by differential-algebraic equations (DAEs).

There is a well-known approach in automata theory called hybrid automata that is able to handle multi-mode systems if the modes are described by ordinary differential equations (ODEs). However, for CPS this approach is not feasible because the physical equations in the form of implicit DAEs must be converted into explicit ODE form, and the number of needed states to do so can grow very rapidly.

Therefore the simulation of mode switching in CPS is a fundamental difficulty that has been recently successfully addressed within the MODRIO project by designing and implementing the prototype of a new Modelica hybrid-state machine in Dymola[1]. The new hybrid state machine generalizes the concept of hybrid automata to systems described by DAEs, with deterministic or stochastic transitions guarded by events (transitions may be instantaneous or delayed, depending on the current state). It also introduces a new dimension in modelling modularity: the ability to add new modes to a model component without modifying existing ones. It is therefore now possible to adapt progressively existing models to simulate dysfunctional situations.

The objective of this paper is to show how the generic problem of phase appearance or disappearance in a thermal-hydraulic volume may be solved using this new prototype.

Nomenclature

ρ	fluid density (kg/m^3)
V	fluid volume (m^3)
$\dot{m}$	fluid mass flow rate (kg/s)
h	fluid specific enthalpy (J/kg)
u	fluid internal energy (J/kg)
x	mass fraction of vapor within the two-phase mixture (-)

Subscripts l refer to the liquid phase. Subscripts v refer to the vapor phase.

2. Classical modelling of one and two-phase fluid

2.1. Staggered grid concept

Fluid systems are described by mass, momentum and energy balance partial differential equations (PDEs) with respect to space and time. These equations, complemented by other equations such as correlations and state equations, describe the physical state of the fluid system, i.e. the distribution of pressure P, temperature T and mass flows $\dot{m}$ throughout the system. In the so-called finite volume approach, the system is discretized into the so-called staggered grid scheme, which is a sequence of volumes that divide the complete volume of the system, and pipes that link two neighboring volumes[2]. The PDEs that describe the scalar field (P and T) are integrated over the volumes, and the PDEs that describe the vectorial field ($\dot{m}$) are integrated over the pipes lengths, yielding DAEs which are best suited to describe the physical behavior of large systems.

In the case of single-phase fluid flow, there is one scalar field and one vectorial field, leading to the so-called 3-equation model. In the case of two-phase fluid flow, there are two scalar fields and two vectorial fields, one for each phase, leading to the so-called 6-equation model. However, it is a common and valid simplification for two-phase flow to consider two scalar fields and only one vectorial field common to both phases, leading to the so-called 5-equation model. To account for special two-phase fluid flow effects affecting the common vectorial field such as phase slip (the difference in velocity between the liquid and the vapor), special correlations are added to the fluid model such as the drift-flux model[3].

Therefore, when switching from one-phase to two-phase, it most often only necessary to consider the switch from one scalar field to two scalar fields, the vectorial field remaining single, therefore the switch from a 3-equation model to a 5-equation model. Therefore, the varying number of states affect only the volumes, not the pipes of the staggered grid scheme.

2.2. Fluid equations for a one-phase volume

Before considering two-phase volumes, let us first examine the simpler case of a one-phase volume. As introduced in §2.1, a volume is an abstract modelling component that contains the mass and energy balance equations. Mass flows enter or leave the volume, and the balance equations are used to compute the mixing values of the fluid density and the fluid internal energy which are in turn used to compute pressure and temperature. Flows are assumed to be positive when entering the volume, and negative when leaving the volume. For sake of clarity and without losing generality, we may assume that all mass flows are liquid.

$$\frac{\partial(\rho_l \cdot V_l)}{\partial t} = \sum_i \dot{m}_{l,i} \tag{1}$$

$$\frac{\partial(\rho_l \cdot V_l \cdot u_l)}{\partial t} = \sum_i h_{l,i} \cdot \dot{m}_{l,i} + W_l \tag{2}$$

Eq. (1) constitutes the mass balance equation. Its role is to compute the mass of fluid of density ρ_l in the mixing volume V_l from the mass flow rates of liquid $\dot{m}_{l,i}$ entering or leaving the volume. The summation is taken over all mass flows entering or leaving the volume. In a similar way, (2) constitutes the energy balance equation. Its role is to compute the specific internal energy u_l of the mixing fluid from the energy flows entering or leaving the volume. There are three kinds of energy flows: the convective flows given by the terms $h_{l,i} \cdot \dot{m}_{l,i}$ carried by the ingoing or outgoing mass flows, the thermal flow W_l entering or leaving the volumes through the walls of the volume, and diffusion (or conduction) due to the difference in temperature between two neighboring volumes (that communicate through a pipe of the staggered grid scheme, as explained in §2.1). Without losing generality, and for sake of simplicity, diffusion is not considered here. Diffusion can be neglected as soon as at least one mass flow rate departs significantly from zero. However, considering diffusion becomes necessary to avoid singularities when considering

the static case (i.e. when the differential terms in (1) and (2) are considered to be zero) and when all mass flow rates go to zero[4].

2.3. Fluid equations for a two-phase volume (drum)

Drums are two-phase cavities where evaporation and condensation take place. Therefore, they are most conveniently modelled as two-phase volumes. They are used in power plants to produce steam for the turbine that is coupled to the electric generator. In the sequel, the words 'drum' and 'two-phase volume' are used synonymously as they represent the same modelling object.

For a two-phase volume, one must first add the balance equations relative to the second phase, i.e. the vapor phase, which are the same than those for the liquid phase. Therefore, only the subscript referring to the phase is changed in (1) and (2) to yield the balance equation for the vapor phase.

$$\frac{\partial(\rho_v \cdot V_v)}{\partial t} = \sum_i \dot{m}_{v,i} \tag{3}$$

$$\frac{\partial(\rho_v \cdot V_v \cdot u_v)}{\partial t} = \sum_i h_{v,i} \cdot \dot{m}_{v,i} + W_v \tag{4}$$

The interactions between the two phases that are related to the mass and energy balance equations should also be taken into account.

The first interaction constrains the volume of liquid and the volume of vapor to the volume of the cavity:

$$V_l + V_v = V \tag{5}$$

As (5) puts an algebraic constraint on the two differential variables V_l and V_v, the two-phase model constituted by equations (1) to (4) becomes a high index problem, and needs special algorithms such as the Pantelides algorithm[5] to be reduced to a zero-index problem, i.e. to ODEs that may be processes by usual numerical solvers.

The second interaction is related to the mass transfer between the two phases. It is important to understand here that each phase taken separately is in fact a mixture of liquid and vapor, and not (in general) a pure liquid or vapor phase. Therefore the liquid phase may contain bubbles and the vapor phase may contain droplets. When the concentration of bubbles in the liquid phase becomes higher than a certain threshold, the bubbles start entering the vapor phase (i.e. the liquid starts to evaporate) until the concentration goes back under the threshold. In the same way, when the concentration of droplets in the vapor phase is higher than a certain threshold, the droplets start entering the liquid phase (i.e. vapor starts to condensate) until the concentration goes back under the threshold. Therefore the liquid phase is a mixture of predominantly liquid phase that contains vapor, and the vapor phase is a mixture of predominantly vapor phase that contains liquid. The mixture is characterized by its vapor mass fraction x_l for the liquid phase (x_l is close to 0), and x_v for the vapor phase (x_v is close to 1). Condensation and evaporation bring additional and energy through convection to the other phase.

The condensation and evaporation flow rates are given by the two following equations:

$$\dot{m}_{cond} = \begin{cases} 0 \; if \;\; x_v > x_{v,0} \\ C_{cond} \cdot \rho_v \cdot V_v \cdot (x_{v,0} - x_v) \; if \;\; x_v \le x_{v,0} \end{cases} \tag{6}$$

$$\dot{m}_{evap} = \begin{cases} 0 \; if \;\; x_l < x_{l,0} \\ C_{evap} \cdot \rho_l \cdot V_l \cdot (x_l - x_{l,0}) \; if \;\; x_l \ge x_{l,0} \end{cases} \tag{7}$$

Eq. (6) and (7) are not first principle physical equations. They are phenomenological equations that consider respectively $x_{v,0}$ and $x_{l,0}$ as the set points of a natural controller for the vapor mass fraction x_v in the vapor phase and the vapor mass fraction x_l in the liquid phase. C_{cond} and C_{evap} are time constants of the controller that must be adjusted manually to account for the condensation and evaporation rates (i.e. how fast evaporation and condensation take place). To the knowledge of the author, these are the only equations available to account for the condensation and evaporation mass flow rates in drums.

3. Modelling phase appearance and disappearance using multi-mode modelling

3.1. Why using multi-mode modelling for phase appearance and disappearance?

Without loss of generality in this discussion, we will consider that vapor is the phase that may appear or disappear. Equations (1) to (4) are DAEs, i.e. equations of the form:

$$A \cdot \dot{x} = f(x, a) \tag{8}$$

where A is a matrix that may not be invertible, x, $\dot{x}$ and a denoting respectively the differential state, the state derivative and the algebraic state. If A is invertible, (8) may be transformed into ODE form that may processed by usual numerical solvers:

$$\dot{x} = A^{-1} \cdot f(x, a) \tag{9}$$

Equation (3) and (4) may be respectively transformed into the following form:

$$\dot{V}_v = \frac{1}{\rho_v} \cdot \left(K - \dot{\rho}_v \cdot V_v\right) \tag{10}$$

$$\dot{u}_v = \frac{1}{\rho_v \cdot V_v} \cdot \left(L - K \cdot u_v\right) \tag{11}$$

with:

$$K = \sum_i \dot{m}_{v,i} \tag{12}$$

$$L = \sum_i h_{v,i} \cdot \dot{m}_{v,i} + W_v \tag{13}$$

When $V_v = 0$, (10) is still a valid ODE as ρ_v never goes to zero (the density is a physical property of the fluid that is independent of its volumetric extension). However, when $V_v = 0$, (11) is not a valid ODE as it becomes singular. Therefore, (11) cannot be used when the vapor phase disappears. The usual workaround to this problem is to replace V_v by a small fixed quantity ε_v when $V_v < \varepsilon_v$ (or equivalently to consider minimum non-zero volume fractions[6]). This solution has two major drawbacks: the numerical system is ill-conditioned, and (11) is kept active in the model although it is not needed as there is no vapor phase. This results in models that are usually not robust, that are slow and difficult to run when the vapor phase disappears. Hence, the reason for using multi-mode modelling is the ability to get rid of (11) when it is not needed, i.e. when the vapor phase is not present. Going back to the original equations, the reason for using multi-mode modelling is the ability to get rid of (2) and (4) when they are not needed.

3.2. Equations for a multi-mode drum

The multi-mode drum contains 3 states: 2 single-phase states corresponding to the one-phase liquid and vapor states, and one two-phase state.

The two-phase state is described by equations (1) to (4). However, in order to avoid a numerical divergence when the liquid or the vapor phase volumes approach zero, the terms W_l and W_v in (2) and (4) must be written as:

$$W_l = w_l \cdot V_l \tag{14}$$

$$W_v = w_v \cdot V_v \tag{15}$$

Eq. (14) and (15) are more realistic in the sense that the amount of external energy brought to a given phase goes to zero when the volume of that phase goes to zero. w_l and w_v are the amount of energy brought to the corresponding phase per volume unit.

The single-phase liquid state is described by equations (1), (2) and (3). The reason for adding (3) is to account for the possibility of growth of the vapor phase inside the liquid phase. Without (3), it would not be possible to represent the appearance of the vapor phase within the liquid phase. It is possible to use (3) even when the volume of the vapor phase is zero, as explained in §3.1.

In the same way, the single-phase vapor state is described by equations (3), (4) and (1).

3.3. The hybrid state model for the multi-mode drum

The hybrid state model for the multi-mode drum is given in Fig. 1.

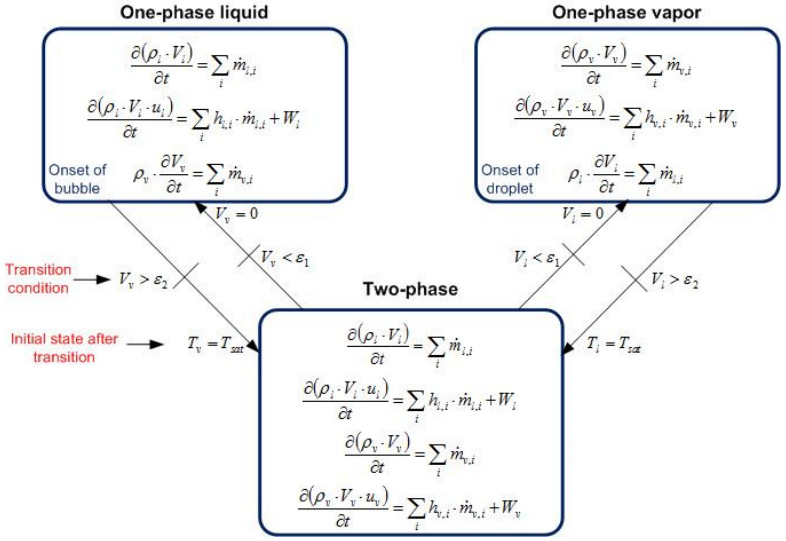

Fig. 1. Hybrid state model for the multi-mode drum.

Note that the equations for the onset of droplets or bubbles are somewhat simplified as they assume that the volume of the appearing phase is zero.

When the volume of the disappearing phase is smaller than a number denoted ε_1 chosen as small as possible (i.e. such as it does not generate a numerical divergence), the state machine undertakes the transition from the two-phase state to the corresponding one-phase state. When entering the one-phase state, the volume of the disappearing phase is set to zero as it should not be kept equal to ε_1. It is necessary to fire the transition before the volume of the disappearing phase reaches zero as the energy balance equations in the two-phase state are not robust to zero volumes.

When the volume of the appearing phase is larger than a number denoted ε_2 also chosen as small as possible, the state machine undertakes the transition from the corresponding one-phase state to the two-phase state. When entering the two-phase state, the temperature of the appearing phase is assumed to be equal to the saturation temperature.

To avoid chattering between two states, ε_1 must be larger than ε_2:

$$\varepsilon_1 > \varepsilon_2 \tag{16}$$

Condition (16) is necessary, but not always sufficient. When starting from a one-phase liquid state the vapor phase starts to grow within the liquid, transition to the two-phase state occurs when the vapor volume exceeds ε_2. However, if the mass flow rate of vapor leaving the drum is higher than the mass flow rate of vapor growing in the liquid phase, the volume of vapor goes rapidly back to zero and the drum goes back to the one-phase liquid state as soon as the volume of vapor is less than ε_1. Consequently, the system oscillates between the one-phase liquid state and the two-phase state at a speed that depends on $\varepsilon_2 - \varepsilon_1$ and on the difference between the vapor mass flow rate at the outlet of the drum and the vaporizing mass flow rate inside the liquid phase. This behavior is not satisfactory and may cause numerical difficulties. To overcome this difficulty the idea is to avoid accumulating vapor in the liquid phase if the mass flow rate $\dot{m}_{evap}$ of the vaporizing water is less than the mass flow rate $\dot{m}_{v,out}$ of the exiting vapor at the drum outlet, so that the system remains in one-phase liquid state as long as there is not enough creation of vapor to keep the system steadily in the two-phase state. The idea is to consider that bubbles that appear within the liquid phase in such conditions go directly to the outlet without accumulating in the liquid phase. To that end, a mass fraction for the appearing vapor phase is introduced:

$$\tilde{x}_v = \begin{cases} \max\left(\min\left(1, \dfrac{\dot{m}_{evap}}{\dot{m}_{v,out}}\right), 0\right) & if\ \ \dot{m}_{v,out} > 0 \\ 0 & else \end{cases} \tag{17}$$

The terms $-(1-\tilde{x}_v)\cdot\dot{m}_{v,out}$, $-(1-\tilde{x}_v)\cdot h_{v,out}\cdot\dot{m}_{v,out}$ and $-\tilde{x}_v\cdot\dot{m}_{v,out}$ are respectively added to the right hand sides of equations (1) to (3), where $h_{v,out}$ is the fluid specific mixing enthalpy at the drum outlet:

$$h_{v,out} = \tilde{x}_v \cdot h_{v,sat} + (1-\tilde{x}_v)\cdot h_l \tag{18}$$

A similar approach is used when bubbles grow in a one-phase vapor state.

3.4. Simulation results

The drum boiler is used in the model of a vaporizing loop. Cold water is injected into the boiler and mixes with the water already inside the boiler. Water inside the boiler circulates through a vaporizing loop that starts at the bottom of the boiler, and is heated to produce a mixture of water and steam that is re-injected into the boiler above the water level. The test scenario consists in applying a periodic variation of the heat flux provided to the vaporizing loop so that the drum boiler goes through all possible three states: two-phase, one-phase liquid (vapor volume equals zero) and one-phase vapor (liquid volume equals zero), as shown in Fig. 2. Simulations are performed using Dymola 2016 FD01.

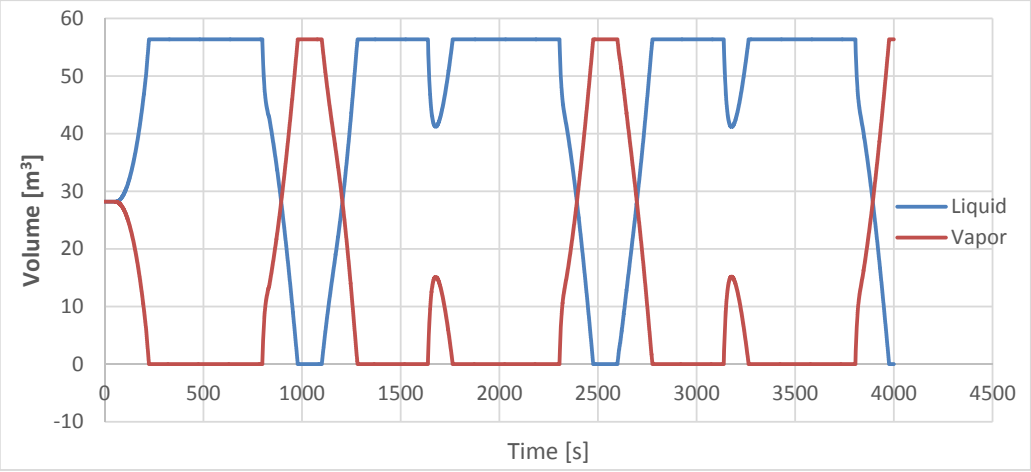

Fig. 2. Drum boiler going through all states.

4. Conclusion and future work

A new approach has been developed for modelling thermal-hydraulics cavities that exhibit phase appearance and disappearance. This new approach uses the new Modelica hybrid state machine developed within the European ITEA 2 MODRIO project and implemented as a prototype in the commercial tool Dymola developed by Dassault-Systèmes. This approach is quite general and its main benefit is that it allows switching from 3-equations models used for single-phase fluid flow modelling to 5-equation models used for two-phase fluid flow modelling, thus bridging the gap between these two types of simulation codes which are in general used for different purposes, 3-equation codes targeting normal operation and 5-equation aiming at dysfunctional or accidental situations. Thus it paves the way to unifying normal and dysfunctional/accidental modelling and simulation.

This multi-mode approach should be extended to handle dynamically reconfigurable systems which are systems with components that may be switched on and off (such as systems in a network of systems), or that may enter and leave the system (such as cars or planes in a traffic system).

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